ACCOUNTS
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Laser Trapping Chemistry: From Polymer Assembly to Amino Acid Crystallization

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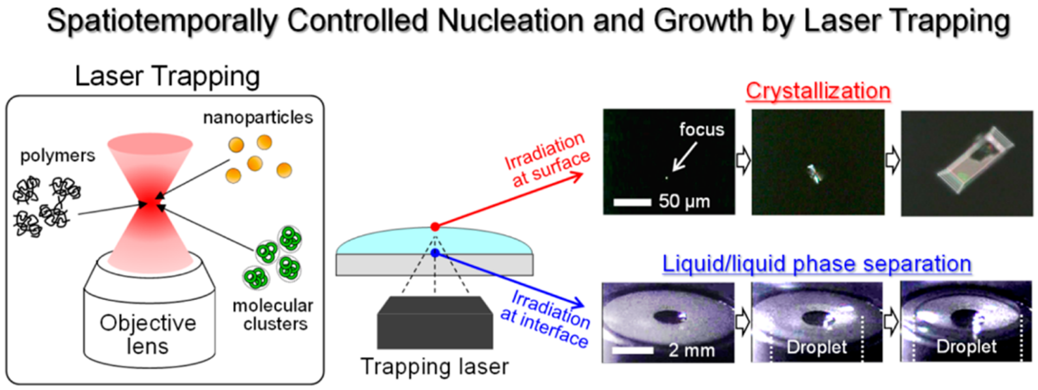
CONSPECTUS



Laser trapping has served as a useful tool in physics and biology, but, before our work, chemists had not paid much attention to this technique because molecules are too small to be trapped in solution at room temperature. In late 1980s, we demonstrated laser trapping of micrometer-sized particles, developed various methodologies for their manipulation, ablation, and patterning in solution, and elucidated their dynamics and mechanism. In the 1990s, we started laser trapping studies on polymers, micelles, dendrimers, and gold, as well as polymer nanoparticles. Many groups also reported laser trapping studies of nanoclusters, DNA, colloidal suspensions, etc. Following these research streams, we have explored new molecular phenomena induced by laser trapping. Gradient force leading to trapping, mass transfer by local heating, and molecular reorientation following laser polarization are intimately coupled with molecular cluster and aggregate formation due to their intermolecular interactions, which depend on whether the trapping position is at the interface/surface or in solution.

In this Account, we summarize our systematic studies on laser trapping chemistry and present some new advances and our future perspectives. We describe the laser trapping of nanoparticles, polymers, and amino acid clusters in solution by focusing a continuous wave 1064 nm laser beam on the molecules of interest and consider their dynamics and mechanism. In dilute solution, nanoparticles with weak mutual interactions are individually trapped at the focal point, while laser trapping of nanoparticles in concentrated solution assembles and confines numerous particles at the focal spot. The assembly of polymers during their laser trapping extends out from the focal point because of the interpolymer interactions, heat transfer, and solvent flow. When the trapping laser is focused at an interface between a thin heavy water solution film of glycine and a glass substrate, the assembled molecules nucleate and evolve to a liquid–liquid phase separation, or they will crystallize if the trapping laser is focused on the solution surface. Laser trapping can induce spatiotemporally the liquid and solid nucleation of glycine, and the dense liquid droplet or crystal formed can grow to a bulk scale. We can control the polymorph of the formed glycine crystal selectively by tuning trapping laser polarization and power. These results provide a new approach to elucidate dynamics and mechanism of crystallization and are the fundamental basis for studying not only enantioselective crystallization but also confined polymerization, trapping dynamics by ultrashort laser pulses, and resonance effect in laser trapping.

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I. Laser Trapping of Individual Nanoparticles

Laser trapping has been applied as a useful tool in physics and biology,[1] while it had not received much attention in chemistry before our work, because molecules are too small to be trapped in solution at room temperature. In the late 1980s, we demonstrated laser trapping of micrometer-sized particles in view of chemistry, developed various methodologies for their manipulation, ablation, and patterning in solution, and elucidated their dynamics.[2] This was the first systematic study on spectroscopy and chemical dynamics and mechanism in small domains as far as we knew. In the middle of the 1990s, we started laser trapping studies on polymers, micelles, dendrimers, and gold, as well as polymer nanoparticles.[3,4] Also nanoclusters,[5] DNA,[6] colloidal suspensions,[7] and so on were reported by many groups. The trapping potential energy exerted on nanometer-sized objects in solution at room temperature is comparable to that of their thermal fluctuation and their individual detection was not easy, so that their trapping experiment was generally difficult. To overcome these problems, we have developed laser trapping systems equipped with a high power trapping laser and various sensitive detectors.

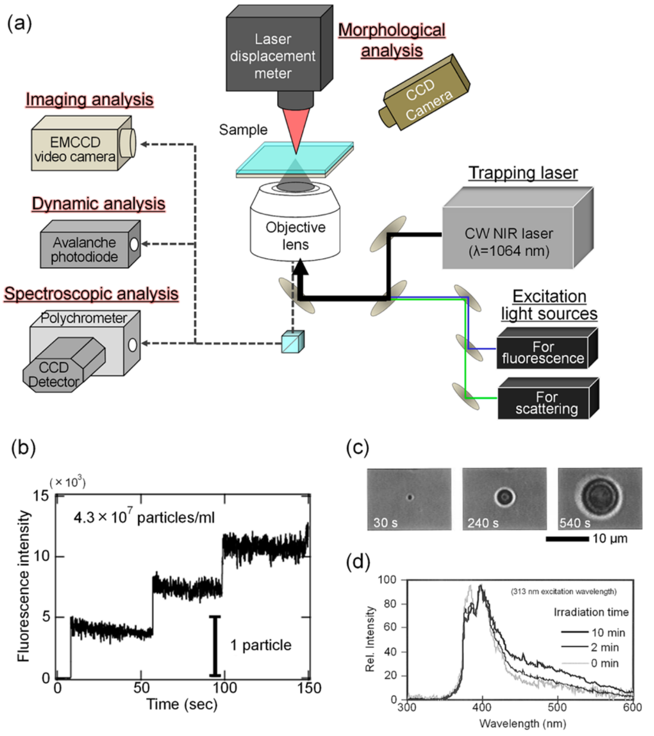


FIGURE 1. (a) Schematic illustration of our representative laser trapping system. (b) Step-by-step trapping dynamics of polystyrene nanoparticles. Panel b reproduced from ref 8. Copyright 2004 The American Physical Society. (c) Photographs and (d) fluorescence spectral change of phase separation of pyrene-labeled PNIPAM and upon its focused irradiation. Panels c and d reproduced from ref 9. Copyright 1997 American Chemical Society.

Our representative trapping system is shown in Figure 1a, where a 1064 nm near-infrared (NIR) continuous-wave (CW) laser is used as a trapping light source and its power can be increased up to ~1 W. Additionally excitation light is introduced for transmission, fluorescence, scattering spectroscopy, and imaging. Trapping dynamics of nanoparticles (Figure 1b) and morphological and fluorescence changes (Figure 1c,d) of pyrene-labeled poly(*N*-isopropylacrylamide) (PNIPAM) during laser trapping are shown as typical data.[8,9] The focal volume of about 1 μm^3 is monitored at the single nanoparticle level, but sometimes a focal plane (~100 μm × 100 μm) is observed. Our sample solutions are mostly transparent in the visible region, but the overtone band of OH vibrational mode of solvents such as water and alcohols absorbs the 1064 nm beam. It was experimentally confirmed that temperature elevation of 20−30 °C in water is brought about at the focal volume upon irradiation with a laser power density of ~100 MW/cm^2.[10] In our experiments, we usually use heavy water as solvent, where temperature elevation is suppressed to be less than a few degrees.

Laser trapping phenomena of a particle with the size larger and smaller than the wavelength are conventionally interpreted by geometrical optics and Maxwell−Boltzmann electromagnetic theory, respectively. Radiation force exerted on nanometer-sized objects is given as follows:[11]

$$F = \frac{1}{2}\varepsilon_m \alpha \nabla \mathbf{E}^2 + \frac{n_m \langle \mathbf{E} \times \mathbf{B} \rangle C_{scat}}{c} \qquad (1)$$

Here **E** and **B** denote the electric field and magnetic flux density, respectively, and ∇ represents a gradient with respect to the spatial coordinates. Parameters of ε_m, n_m, C_{scat}, and c represent the permittivity of the surrounding medium, its refractive index, light scattering cross section of the nanoparticle, and speed of light in vacuum, respectively. The polarizability of the nanoparticle, α, under the dipole approximation is given by

$$\alpha = 4\pi r^3 \frac{\left(\frac{n_p}{n_m}\right)^2 - 1}{\left(\frac{n_p}{n_m}\right)^2 + 2} \qquad (2)$$

Notations of r and n_p are the radius and the refractive index of the nanoparticle, respectively. The gradient force of radiation pressure is given as the first term of eq 1, while the scattering force is in the second term of eq 1, which is derived from the change in the direction of the Poynting vector of the electromagnetic wave. As expressed in eq 1, the gradient force is proportional to the gradient of light intensity, while the scattering force is proportional to the Poynting vector and the direction is identical with that of the beam. According to the theory, the size of nanoparticle that can be trapped in aqueous solution at room temperature is estimated to be 3 and 8 nm for gold nanoparticles and polystyrene beads, respectively. Experimentally this estimation was proven by trapping a copolymer of poly(sodium 2-(acrylamide-2-methylpropanesulfonate) (AMPS) and *N*-cyclododecylmethacrylamide giving unimolecular micelles of 5.5 nm with negative charge.[12] Also similar copolymers having a carbazolyl chromophore whose radius of gyration ranges between 10 and 20 nm were trapped successfully.[13]

Early studies on laser trapping of nanometer-sized small objects were carried out for individual gold nanoparticles and polymer beads doped with fluorescent probe molecules, because their respective local plasmon resonance and fluorescence enable us to conduct chemical patterning experiments at the single nanoparticle level. We trapped single 80 nm gold nanoparticles with a 1064 nm laser, induced their transient local heating by irradiating the nanoparticles with a 355 nm nanosecond pulse, and adhered them to a substrate, forming an array.[14] The patterning was performed with the accuracy of a few tens of nanometers,[15] which is useful enough for a patterning method in solution at room temperature. When two gold nanoparticles were trapped and fixed, their anisotropic arrangement was demonstrated by changing the polarization of the trapping laser.[16] Another patterning and fixation experiment was shown for 220 nm polymer beads in solution by combining laser trapping with UV laser-induced local photopolymerization.[17] For spectroscopic analysis at the single nanoparticle level, hyper-Rayleigh and hyper-Raman scattering measurements were carried out for trapped silver nanoparticles with adsorbed dyes.[18,19]

As the next step, we considered that laser-trapping-induced assembly of molecules and polymers is more interesting as a chemical phenomenon.[3,4] The 1064 nm laser irradiation gathers nanoparticles in solution and fills up the focal volume, leading to their assembly. Upon switching off the laser beam, gathered nanoparticles are dispersed again, which shows that laser trapping is a reversible phenomenon. In the case of molecules and polymers in solution, however, laser trapping phenomena are strongly affected by their chemical properties and mutual interactions. In this Account, these laser-trapping-induced phenomena are summarized, new advances are presented, and our perspective is discussed.

II. Laser Assembling of Polymers

For linear polymers of molecular weight 10^5-10^6, the radius of gyration typically reaches a few nanometers, so a gradient force is exerted even on single polymers. These polymers can be trapped and associated with each other, the volume is increased resulting in a stronger gradient force, and eventually the whole focal volume is filled by the polymers.[20,21] This trapping picture was clearly confirmed by using fluorescent polymer beads as a probe for fluorescence correlation spectroscopy. The fluorescence intensity of 100 nm beads in the dilute suspension gives a stepwise increase in Figure 1b, indicating sequential single bead trapping. The systematic analysis revealed that the initial assembly rate was proportional to the laser power and concentration of particle suspensions as expected from the diffusion equation. By analysis of fluorescence behavior of the 40 nm bead suspensions, trapping, association, and the following detrapping of a few polymer beads were confirmed.[8] Furthermore, it was demonstrated that about a thousand 24 nm beads were confined in an optical potential forming the large aggregate, which exhibited harmonic oscillation in the optical potential.[22]

The trapping force with a few hundred milliwatts laser is strong enough to suppress the mutual electrostatic repulsion among the repulsive charged unimolecular micelles.[12] The trapping rate is larger for polymers containing aromatic substituents, because the polarizability of π-bonds in molecules is higher than that of σ-bonds.[13] PNIPAM is dissolved in water through the hydrogen bonding network with solvent, while radiation pressure is strong enough for breaking the network. These results were obtained by correlating trapping behavior of the polymers with their structures.[9,23]

Usually laser trapping assembly takes place at and around the focal point but sometimes extends up to a few tens of micrometers, which is made possible by coupling of laser trapping with heat transfer, solvent flow, or mutual intermolecular interactions. As mentioned above, laser trapping in aqueous solution sometimes results in temperature elevation of 20−30 °C in the focal volume, and the local heating expands to the surrounding area of a few tens of micrometers. This phenomenon was visualized by using temperature-dependent phase transition of PNIPAM,[9] as shown in Figure 1c. The coupling of laser trapping with local

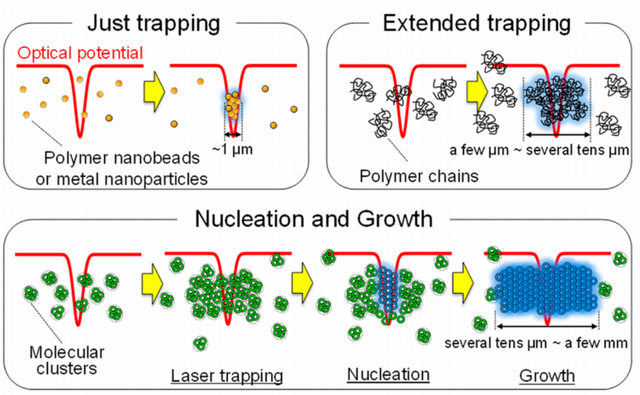


FIGURE 2. Schematic illustrations for trapping and assembly of nanoparticles, polymers, and molecular clusters.

flow of solution was studied for poly(2,7-(9,9-bis(2-ethylhexyl)fluorene)) in tetrahydrofuran.[24] The single fibril-like assembly was grown along the flow and became far longer than the focal size, and the polymers in the assembly were oriented according to the trapping laser polarization. In a nematic liquid crystal film, the molecular reorientation started at the focal position upon laser irradiation and propagated up to a few tens of micrometers. This propagation behavior is ascribed to strong intermolecular interactions characteristic of liquid crystals, and the original and laser-induced orientations are balanced at their border.[25]

The trapping and assembly behaviors of nanoparticles, polymers, and molecular clusters are schematically summarized in Figure 2. Polymer nanobeads and metal nanoparticles are confined at the focal volume, while laser trapping assembly of polymers is extended to its outside due to intermolecular interactions, heat transfer, and solvent flow. In the case of liquid crystals, laser-induced local reorientation starting at the focus is stopped at a certain distance. When trapping and assembly induce nucleation, such an alignment at the focal volume can extend further even to a bulk scale. Indeed we demonstrated that liquid and solid nucleations of glycine in heavy water triggered at the focal volume evolve to liquid–liquid phase separation (LLPS) and crystallization, respectively.

III. Laser Trapping-Induced Liquid–Liquid Phase Separation

When an intense trapping laser is focused within a thin solution film with the thickness of a few hundreds of micrometers, surface deformation is caused by the reduction of the surface tension due to laser heating, and local convection is induced in parallel, leaving an ultrathin film of a few micrometers. When polymers are dissolved, their mass transfer to the depressed area takes place and radiation pressure acts on the gathered polymers. As a result, the efficient laser trapping of polymers is achieved and the aggregates are eventually deposited on the glass through solvent evaporation.[26] This ultrathin film formation and polymer deposition are schematically illustrated in Figure 3a (upper right). Louchev et al. theoretically examined this result and reported that the mass transfer is increased by 1 or 2 orders of magnitude compared with that before irradiation.[27]

By focusing the trapping laser to the solution/glass interface, we have recently succeeded in demonstrating spatiotemporally controlled LLPS for a thin film of glycine supersaturated D_2O solution.[28,29] A schematic illustration of this phenomenon is given in Figure 3a (lower right), while the temporal change of the 2D-surface profile and the corresponding CCD images are summarized in Figure 3b. It is considered that glycine in the concentrated D_2O solution forms liquid-like clusters, in which solute and solvent molecules are weakly linked with each other.[30,31] Their size is a few nanometers and the aggregates of the clusters are large enough to be trapped. Their laser trapping increases the concentration, triggering nucleation of a liquid region. The clusters are continuously supplied to the depressed area by further irradiation, a nucleus grows larger and larger by absorbing the clusters, and eventually a convex-shaped thin liquid dense droplet is formed, laterally reaching the millimeter scale.[29] No solvent evaporation takes place and no rupture of the film is observed unlike in the above polymer solution. The formed liquid droplet is stably observed till the trapping laser is switched off.

LLPS is generally triggered by homogeneous concentration increase due to supercooling of the solution and a number of nucleation events should take place in the whole solution. On the other hand, in the laser-trapping-induced LLPS, the high concentration area is locally generated at the focal spot, and a single liquid nucleus is prepared and followed by its growth. The high concentration area propagates to the outside from the focal spot, expanding up to the millimeter size. We demonstrated that the formation and dissolution of the droplet are well controlled by switching on and off the trapping laser, respectively. When the trapping laser is shifted from the center of the prepared single droplet to its outside, the front side of the droplet extends toward the new focal point, while the opposite side undergoes dissolution. As a result, the droplet is transferred in the direction of the new focal point in the thin liquid film as shown in Figure 3c. All processes of formation, dissolution, and regrowth of local inhomogeneous concentration area are

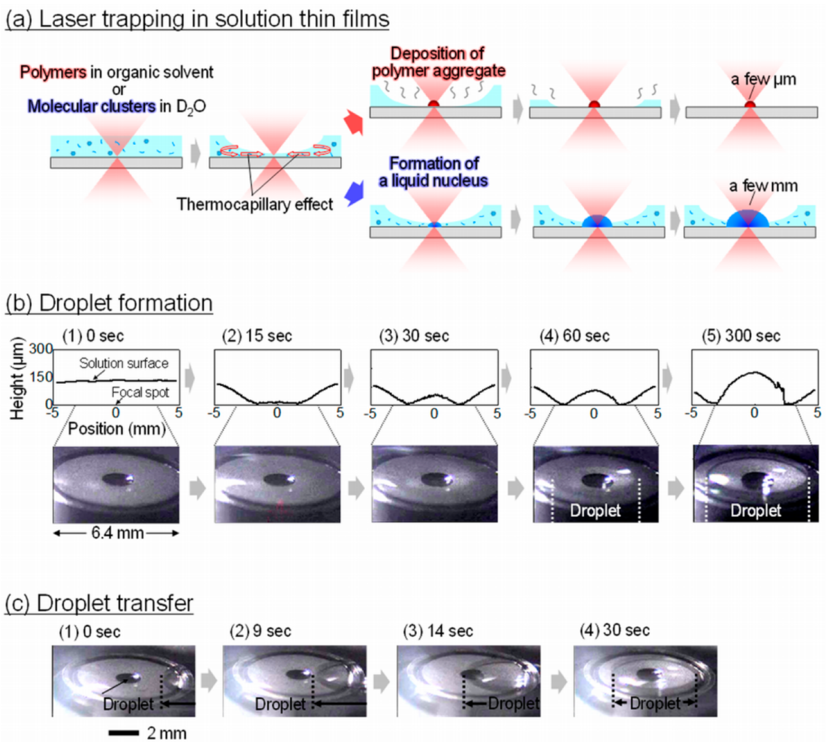


FIGURE 3. (a) Schematic illustration of laser trapping in solution thin films. (b) Formation and (c) transfer of glycine dense liquid droplet by laser trapping of the liquid-like clusters. Panels b and c reproduced from ref 29. Copyright 2012 American Chemical Society.

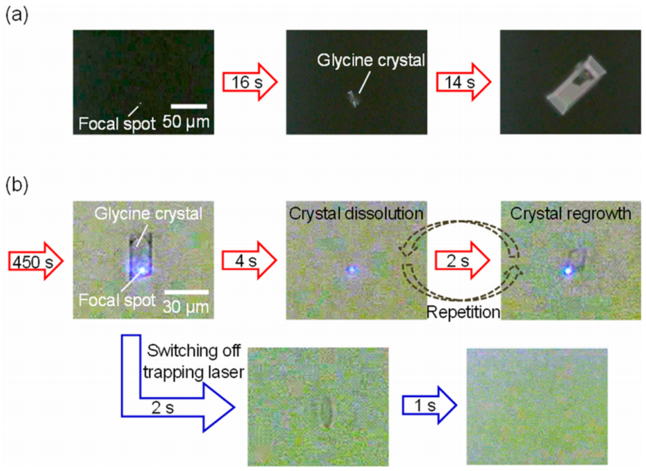


FIGURE 4. Representative behavior of laser trapping crystallization of glycine (a) in a supersaturated solution and (b) in an unsaturated solution. Panel b reproduced from ref 36. Copyright 2010 American Chemical Society.

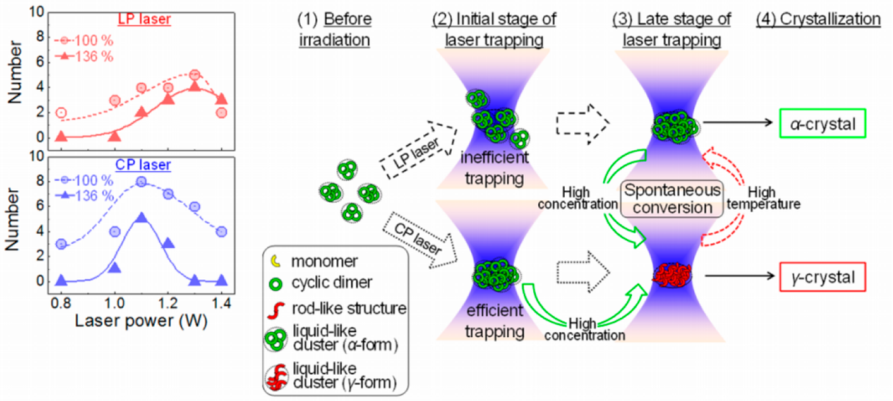
spatiotemporally controlled by the trapping laser, and a single high concentration region can be formed and transferred in a thin solution film.

IV. Laser Trapping Crystallization

When the trapping laser was focused at the air/solution interface of the supersaturated glycine in D_2O, we found its crystallization instead of LLPS.[32] The result is shown in Figure 4a, where the single crystal with a visible size appeared at the focal point in a few tens of seconds after starting irradiation. We consider that the solid nucleation occurs at the solution surface instead of liquid nucleation at the solution/glass interface, which is probably ascribed to molecular alignment characteristics of the surface. The present LLPS and crystallization are well explained in terms of two order parameters of molecular concentration and association structure.[33−35] Laser trapping crystallization study is useful for revealing crystallization dynamics and mechanism.

Generally crystallization takes place in supersaturated solution, which is attained by solvent evaporation, cooling of solution, and so on, but never in unsaturated solution. However laser trapping forms a transient and local supersaturated region around the focal point, so that it makes it possible to crystallize glycine even in its unsaturated solution. The representative example is given in Figure 4b, where the laser beam was focused at the solution surface of the unsaturated (50%) glycine solution.[36] One single crystal rapidly grew up to about 30 μm after incubation time of a few minutes and underwent dissolution within 4 s. Then a few micrometers sized crystal was generated again. Such interesting behavior of crystal growth and dissolution was repetitively induced in a random manner. The generated crystal always grew larger than the focal spot size of about 1 μm,

(a) Supersaturated/saturated solutions



(b) Unsaturated solution

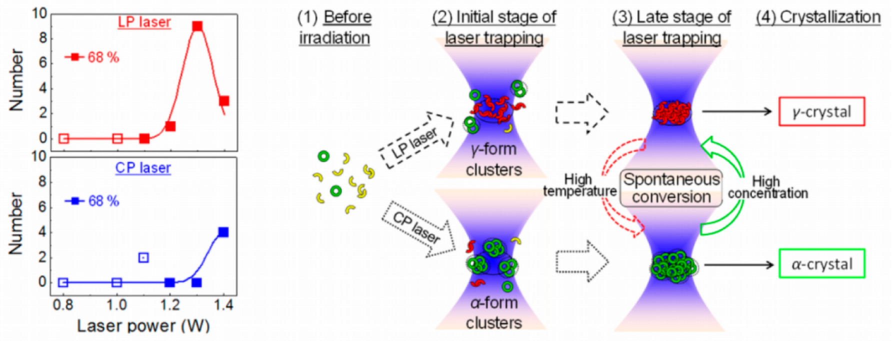


FIGURE 5. The probability of γ-form and its mechanism as a function of laser polarization and power (a) in the supersaturated/saturated solution and (b) in the unsaturated solution. The sample number crystallized into γ-form is shown on the left side. Filled symbols show the 100% crystallization probability, while unfilled marks correspond to the lower probability. The mechanism of polymorph control is schematically illustrated on the right side. A part of this figure reproduced from ref 46. Copyright 2012 American Chemical Society.

and particularly the first crystal was the largest. Hence, it is considered that the concentrated area already expands to outside of the focal volume before crystallization and that the size of the generated crystal indicates how large the saturated area is prepared in a few minutes. Laser trapping crystallization in unsaturated solution will enable us to expand crystallization conditions of concentration, temperature, and so on, to observe crystal formation dynamics, and to elucidate crystallization mechanism. In our group, laser trapping crystallization is now examined for L-proline, alanine, and other amino acids, and also protein crystallization is being tried.[37]

V. Laser Control of Crystal Polymorph

Identifying the crystal polymorph is always one of the important issues in crystallization studies, and it is recognized to depend on the concentration of solution and molecular alignment in the nucleation stage. The glycine crystal has several polymorphs, among which α- and γ-crystals have cyclic unit of glycine dimer and glycine helical chain, respectively.[38,39] It is reasonable to consider that α- and γ-crystals are grown from respective liquid-like clusters, α-cluster with a cyclic dimer structure giving a disk-like polarizability and γ-cluster with a helical chain structure giving a rod-like polarizability.[40] α-Clusters are usually formed in saturated and supersaturated solutions, so that α-crystal is kinetically prepared in spontaneous crystallization.[41] γ-Crystal is thermodynamically preferred in solution with high supersaturation value (SS), which is realized by very slow evaporation, tuning pH, or adding salts.[42−44] On the other hand, it is reasonable to consider that α- and γ-clusters respond to circularly polarized (CP) and linearly polarized (LP) laser irradiation, respectively. Thus we demonstrated that laser trapping crystallization should be very useful to control glycine crystal polymorph through its high potential in increasing local concentration and orienting molecules at the focal volume. In the past few years, we have carried out a series of trapping crystallization experiments of supersaturated, saturated, and unsaturated solutions of glycine and analyzed the results as functions of laser polarization and laser power.[45,46]

Figure 5a gives the preparation probability of γ-crystal in the saturated/supersaturated solutions as a function of LP and CP laser power. Because the concentration is high, α-glycine clusters are formed already before irradiation, so they are trapped both with CP and LP lasers, giving α-crystals. Indeed the γ-crystal probability is zero or low below 1 W. The concentration at the focus is increased with laser power, and then α-clusters are possibly converted to γ-clusters at the focus, giving γ-crystal with a certain probability. By further increase in laser power, solution temperature is elevated due to absorption of the 1064 nm laser by glycine molecules themselves, leading to the decrease in SS. Thus the γ-probability shows a bell-shaped dependence on laser power. Since the CP laser irradiation is more efficient to trap α-clusters, the probability peak for CP laser is shifted to the relatively lower power region compared with that of LP laser. Namely, laser polarization dependent gathering and structural rearrangement of glycine clusters are important in laser trapping crystallization. A similar relation between irradiation laser polarization and formed α/γ polymorph was reported for nanosecond laser experiments in the supersaturated aqueous solution by Garetz and Myerson et al.[37] In their experiments, the laser was not focused in the supersaturated solution, so only molecular reorientation depending on laser polarization is critical for triggering the crystallization.

In the case of unsaturated solution, most glycine molecules are dissolved as a monomer and evolve to α- and γ-clusters by laser trapping with CP and LP beams, respectively. As shown in Figure 5b, high power irradiation with LP laser at 1.3 W gives high γ-crystal probability and further increase in the power gives a decrease due to heating effect. In the case of CP laser irradiation, formation of α-clusters efficiently gives α-crystal kinetically. However, very high concentration of α-clusters sometimes results in their spontaneous conversion to γ-clusters as mentioned above, eventually leading to γ-crystals. This is because as γ-clusters are more stable than α-clusters with high SS. It is considered that laser polarization dependent molecular alignment in the clusters is effectively achieved at the air/surface in unsaturated solution. We conclude that the coupling of laser polarization-induced orientation with molecular alignment characteristics of surfaces is an important factor for polymorph control.

Another successful example of molecular alignment control by radiation pressure leading to a unique association structure was given for deposited pseudoisocyanine *J*-aggregates. The fixed aggregates show a narrower fluorescence band compared with that just deposited, indicating highly ordered *J*-aggregate are selectively confined in the focal point.[47] Molecular alignment control by laser trapping is very effective, sometimes changing the intrinsic molecular assembled structure. We believe that optical control of molecular orientation at the nucleation stage is critical and can be achieved by trapping laser, along which we are extending our studies.

VI. Summary and Future Perspective

Radiation pressure of a focused CW NIR laser beam in solution traps polymers, polymer beads, and metal nanoparticles and forms their assemblies at and around the focal point. It also induces liquid and solid nucleation in glycine solution leading to phase separation and crystallization, respectively. It is also worth noting that laser irradiation at the focal volume of about 1 μm^3 is amplified to give a single dense liquid droplet or a single crystal of $\sim 10^5\ \mu m^3$ volume. The results summarized are unique, proposing promising methodologies and providing new viewpoints on assembling and nucleation phenomena. Now recent developments on other molecular trapping phenomena are introduced below, on which we consider future advances in laser trapping chemistry.

Laser trapping dynamics is usually analyzed by monitoring the process at and around the focal point, while direct observation outside the focal point is indispensable to understand whole trapping behaviors. We developed a wide-field Rayleigh scattering spectroscopy and imaging method and observed a convection phenomenon accompanying laser trapping by using gold nanoparticle as a probe. Directional diffusion and trapping processes of gold nanoparticles were examined at single nanoparticle level and considered.[48]

A significant issue in laser trapping chemistry is controlling chemical reactions by radiation pressure. We focused our attention on the polymerization reaction, because conventional molecules are too small to be trapped while polymers can be gathered at a focal point. A one-photon UV polymerization of liquid acrylate solutions was induced in the optical trapping potential of a 1064 nm laser, giving small structures with a volume of less than or equal to a fifth part of the wavelength of the NIR laser beam. This approach has realized the smallest solidification volume as one-photon polymerization and enables us to fabricate tiny polymeric structures smaller than the diffraction limit of the UV light. This is the first demonstration of a radiation pressure effect on photochemical reaction.[49]

Recently, we reported that a novel scattering behavior of polystyrene nanoparticles is induced by femtosecond laser irradiation in addition to their stable trapping. Based on this novel result, we proposed that the axial electric field of the focused ultrashort laser pulses generates lateral scattering and temporal forces.[50] Also stable confinement of quantum dots and the split trapping of gold nanoparticles are achieved by femtosecond laser trapping.[51,52] These results point out a promising future of femtosecond trapping study.

In addition to the present laser trapping crystallization, femtosecond laser-induced bubbling crystallization[53] and CW laser-induced bubbling crystallization on a thin gold film[54] have been reported as laser-induced crystallization. Some important proteins and even a membrane protein were successfully crystallized by the former crystallization method,[55] while the latter was recently demonstrated for glycine solution. The features common to all the laser-induced crystallization phenomena are summarized as follows: Efficient crystallization is made possible at the solution surface or at the surface of laser-formed bubbles in solution, and crystallization is closely related to the formation of a dense liquid droplet. Because crystallization can be induced at any time at any position by the trapping beam, laser trapping crystallization is promising to study the roles of the surface and the droplet, and eventually considered to have high potential in elucidating crystallization dynamics and mechanism.

As a future challenge of laser trapping chemistry and crystallization of molecules, we plan to apply the trapping technique for enantioselective crystallization in spontaneous resolution and from achiral molecules, which are being started. This approach will be contributory to the elucidation of homochirality in the origin of life. Another promising viewpoint of laser trapping is "resonance effect". Indeed, by additionally introducing a visible light that is resonant with the absorption band of a dye doped in the polymer nanobeads, we found that laser trapping of the polymer nanobeads by a 1064 nm trapping laser is enhanced in solution.[56] Similar enhancement of trapping force by the resonant light was also reported experimentally and theoretically.[57,58] Detailed trapping studies on individual nanoparticles of a few nanometers and hopefully molecules will be made possible by utilizing the resonance effect. A certain nanoparticle will be chosen from several codissolved nanotargets by tuning the resonance wavelength, which is indeed a milestone for developing individual molecular trapping in solution. These studies will contribute to the development of laser trapping chemistry.

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BIOGRAPHICAL INFORMATION

Teruki Sugiyama received his Ph.D. from Nankai University, P.R. China, in 2002. He was a Postdoctoral Fellow and then appointed Assistant Professor in Department of Applied Physics at Osaka University in Japan under the supervision of Professor Hiroshi Masuhara. He studied fabrication of organic nanoparticles utilizing laser ablation technique in solution from 2002 to 2006. He became a Researcher at Hamano Life Science Research Foundation in 2007, where he started his current research of a new topic in laser trapping crystallization of organic compounds and proteins. From 2008 to 2011, he worked at Nara Institute of Science and Technology as a Research Associate Professor, and now he is extending his research in Instrument Technology Research Center, National Applied Research Laboratories in Taiwan.

Ken-ichi Yuyama received his B.S. (2004) and M.S. (2006) from Osaka University and Ph.D. from Nara Institute Science and Technology (2011) under the supervisions of Professors Hiroshi Masuhara and Teruki Sugiyama. His Ph.D. thesis was focused on the formation dynamics and mechanism of single dense liquid droplets and crystals achieved by laser trapping technique. In 2011, he took on a postdoctoral fellowship at Department of Applied Chemistry and Institute of Molecular Science, National Chiao Tung University.

Hiroshi Masuhara graduated from Tohoku University in Sendai in 1966 and received his Ph.D. in 1971 at Osaka University. Since 1984, he has had his own laboratory in Kyoto Institute of Technology, Osaka University, Hamano Life Science Research Foundation, and then Nara Institute of Science and Technology, while he was also the director of ERATO Masuhara Microphotoconversion Project, JST, from 1988 to 1993. Now he is conducting his research in National Chiao Tung University in Taiwan.

FOOTNOTES

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The authors declare no competing financial interest.

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